

# Vector Dark Matter Via Higgs Portal

In collaboration with:  
Paddy Fox and Tim M.P. Tait  
[arXiv:1509:XXXXX](#)

## Searching for MeV-Scale Gauge Bosons with IceCube

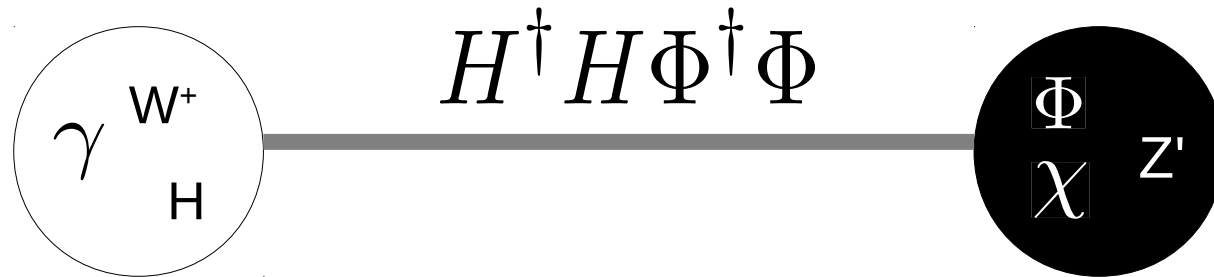
In collaboration with:  
Dan Hooper  
[arXiv:1507.03015](#)



Anthony DiFranzo  
UC Irvine/Fermilab



# The Higgs Portal



- $H^\dagger H$  is a low dimension, SM singlet
- Relates DM to Weak scale, without requiring EW charges

$$H^\dagger H \Phi^\dagger \Phi$$

Scalar Portal:

**Dim-4**

**Gauge invariant**

$$H^\dagger H \bar{\psi} \psi$$

Fermion Portal:

**Dim-5**

**Gauge invariant**

# Vector DM Higgs Portal

$$\mathcal{L} \supset \lambda_{hVV} H^\dagger H V^\mu V_\mu$$

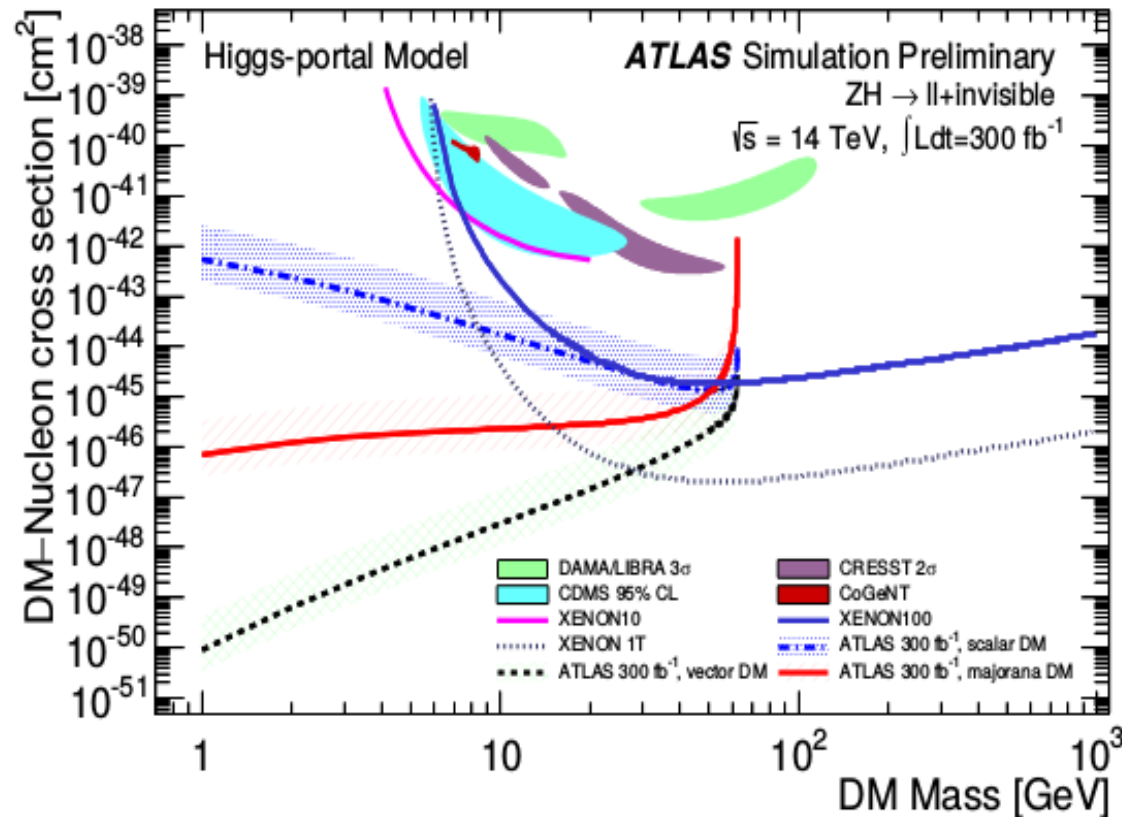
- **dim-4**, but **not gauge invariant**. Should be treated as an EFT.
- Observables have unphysical behavior

$$\sigma_{V-N}^{SI} = \frac{\lambda_{hVV}^2}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_V + m_N)^2}$$

$$\Gamma_{h \rightarrow VV}^{\text{inv}} = \frac{\lambda_{hVV}^2 v^2 m_h^3 \beta_V}{256\pi M_V^4} \left( 1 - 4 \frac{M_V^2}{m_h^2} + 12 \frac{M_V^4}{m_h^4} \right)$$

Djouadi et.al. [arXiv: 1112.3299]

# Higgs width in direct detection plane



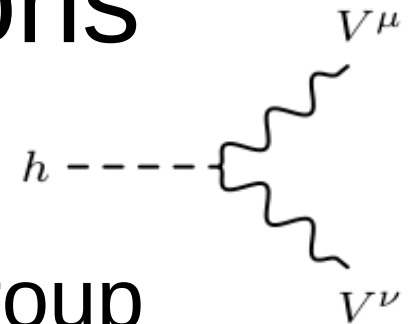
taking ATLAS 14TeV 300fb-1 90%CL sensitivity:  $\text{BR}(h \rightarrow \text{inv}) < 0.19$

ATLAS Collaboration [arXiv: 1402.3244]

See also:

CMS Collaboration [arXiv: 1404.1344]

# UV-complete constructions



- 1) Charge Higgs under dark gauge group
- 2) Introduce new scalar which mixes with Higgs

$$D^\mu \Phi^\dagger D_\mu \Phi, H^\dagger H \Phi^\dagger \Phi \rightarrow \sin \theta \ h V^\mu V_\mu$$

$hVV$  coupling related to  $V$  mass, giving expected behavior in observables

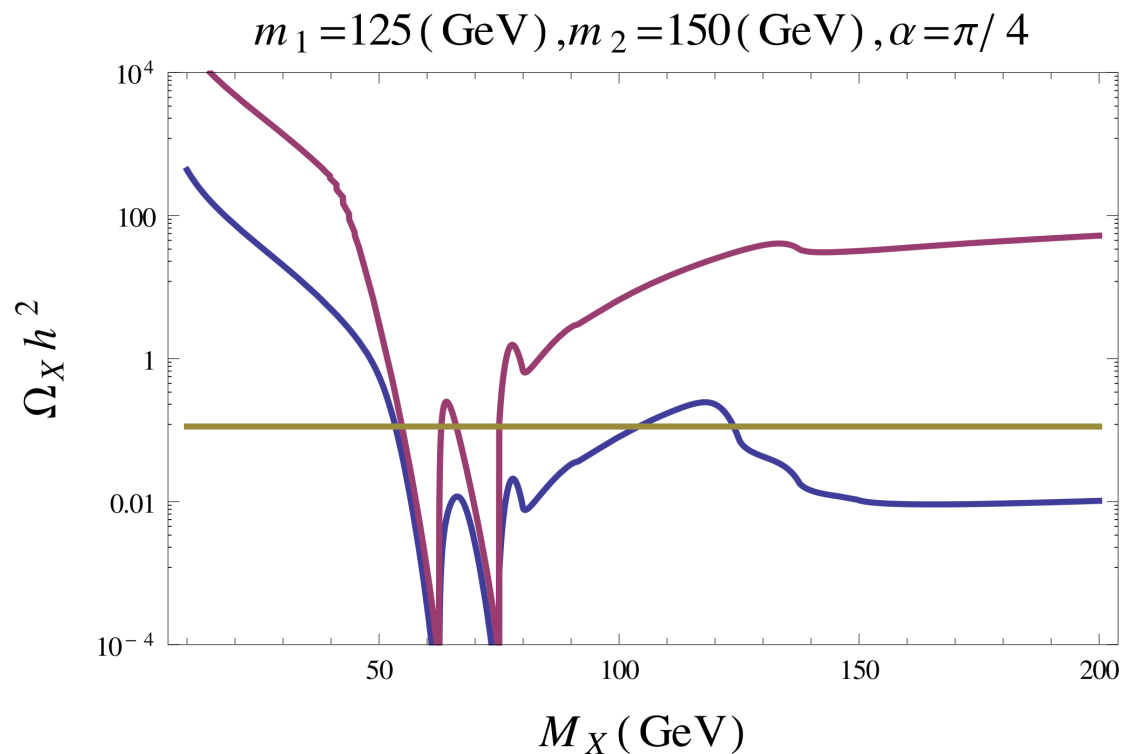


e.g. Baek et.al. [arXiv:1212.2131], Farzan et.al. [arXiv:1207:4272], Hambye [arXiv:0811.0172]

- 3) Radiatively generated

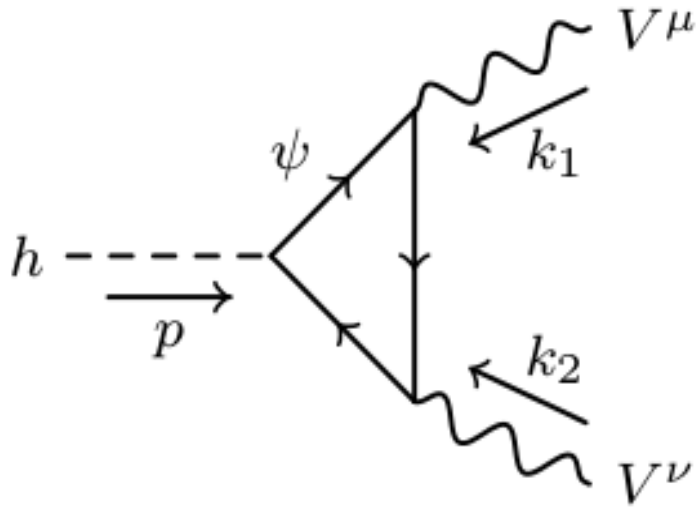
# The Higgs Portal-Portal

$$D^\mu \Phi^\dagger D_\mu \Phi, H^\dagger H \Phi^\dagger \Phi \rightarrow \sin \theta \, h V^\mu V_\mu \\ + \cos \theta \, h_2 V^\mu V_\mu$$



Baek et.al. [arxiv:1212.2131]

# A Toy Model



- Imagine integrating out a heavy fermion
- Similar to hGG/hFF, except:
  - Vector is massive, resulting in term 'B'
  - Yukawa not simply related to fermion mass

$$\mathcal{L}_{loop} = -\frac{1}{4}AhV^{\mu\nu}V_{\mu\nu} - \frac{1}{2}BhV^\mu V_\mu$$

$$A, B \sim \frac{y_\psi}{m_\psi} \neq \frac{1}{v}$$

# UV completion: Requirements

- 1) Anomaly free
- 2) Ensure stability of DM candidate (e.g. prevent kinetic mixing with SM gauge groups)
- 3) visible Higgs width is unaffected (e.g. gluons/photons)

# UV Completion: Matter content

	(SU(2), U(1), U(1)')		(SU(2), U(1), U(1)')	
$\psi_{1\alpha}$	$(2, 1/2, Q)$	$\longleftrightarrow$	$\psi_{2\alpha}$	$(2, 1/2, -Q)$
$\chi_{1\alpha}$	$(2, -1/2, -Q)$	$\longleftrightarrow$	$\chi_{2\alpha}$	$(2, -1/2, Q)$
$n_{1\alpha}$	$(1, 0, -Q)$	$\longleftrightarrow$	$n_{2\alpha}$	$(1, 0, Q)$
$\Phi$	$(1, 0, NQ)$			

$$\begin{aligned}
 -\mathcal{L}_{int} = & m(\epsilon^{ab}\psi_{1a}\chi_{1b} + \epsilon^{ab}\psi_{2a}\chi_{2b}) + m_n n_1 n_2 \\
 & + y_\psi (\underbrace{\epsilon^{ab}\psi_{1a}H_b n_1 + \epsilon^{ab}\psi_{2a}H_b n_2}_{\text{}}) + y_\chi (\chi_1 H^* n_1 + \chi_2 H^* n_2) + h.c.
 \end{aligned}$$

**1) Anomalies are canceled within these pairs**

**2) U(1)' charge conjugation symmetry protects kinetic mixing**

**3) Higgs doesn't interact with new charged fermions**

# Matter after EWSB

$$-\mathcal{L}_{int} = m(\epsilon^{ab}\psi_{1a}\chi_{1b} + \epsilon^{ab}\psi_{2a}\chi_{2b}) + m_n n_1 n_2 \\ + y_\psi(\epsilon^{ab}\psi_{1a}H_b n_1 + \epsilon^{ab}\psi_{2a}H_b n_2) + y_\chi(\chi_1 H^* n_1 + \chi_2 H^* n_2) + h.c.$$

Gives rise to 3 Neutral and 2 Charged Dirac Fermions:

$$-\mathcal{L}_m = N M_n N' + E M_e E' + h.c.$$

$$N = \begin{bmatrix} \psi_{1n} \\ \chi_{2n} \\ n_2 \end{bmatrix}, \quad N' = \begin{bmatrix} \psi_{2n} \\ \chi_{1n} \\ n_1 \end{bmatrix}, \quad E = \begin{bmatrix} \psi_{1e} \\ \chi_{2e} \end{bmatrix}, \quad E' = \begin{bmatrix} \chi_{1e} \\ \psi_{2e} \end{bmatrix}$$

$$M_n = \begin{bmatrix} 0 & -m & -y_\psi v/\sqrt{2} \\ -m & 0 & y_\chi v/\sqrt{2} \\ -y_\psi v/\sqrt{2} & y_\chi v/\sqrt{2} & m_n \end{bmatrix}, \quad M_e = \begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix}$$

# UV Completion: Purpose of Scalar

	(SU(2), U(1), U(1)')		(SU(2), U(1), U(1)')
$\psi_{1\alpha}$	$(2, 1/2, Q)$	$\psi_{2\alpha}$	$(2, 1/2, -Q)$
$\chi_{1\alpha}$	$(2, -1/2, -Q)$	$\chi_{2\alpha}$	$(2, -1/2, Q)$
$n_{1\alpha}$	$(1, 0, -Q)$	$n_{2\alpha}$	$(1, 0, Q)$
$\Phi$	$(1, 0, NQ)$		

- Solely to break U(1)'
- But could also:
  - Cause new fermions to mix with SM leptons ( $N=\pm 1$ )
  - Contribute to mixing between new fermions ( $N=\pm 2$ )
  - Mix with Higgs

$$\lambda H^\dagger H \Phi^\dagger \Phi$$

# Observables from Toy Model

$$\Gamma(h \rightarrow VV) = \frac{\sqrt{1 - 4m_V^2/m_h^2}}{64\pi m_h} \left[ |A|^2 m_h^4 \left( 1 - 4\frac{m_V^2}{m_h^2} + 6\frac{m_V^4}{m_h^4} \right) + 3(A^*B + AB^*)m_h^2 \left( 1 - 2\frac{m_V^2}{m_h^2} \right) + \frac{1}{2} \underbrace{|B|^2}_{\text{blue}} \frac{m_h^4}{m_V^4} \left( 1 - 4\frac{m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4} \right) \right]$$



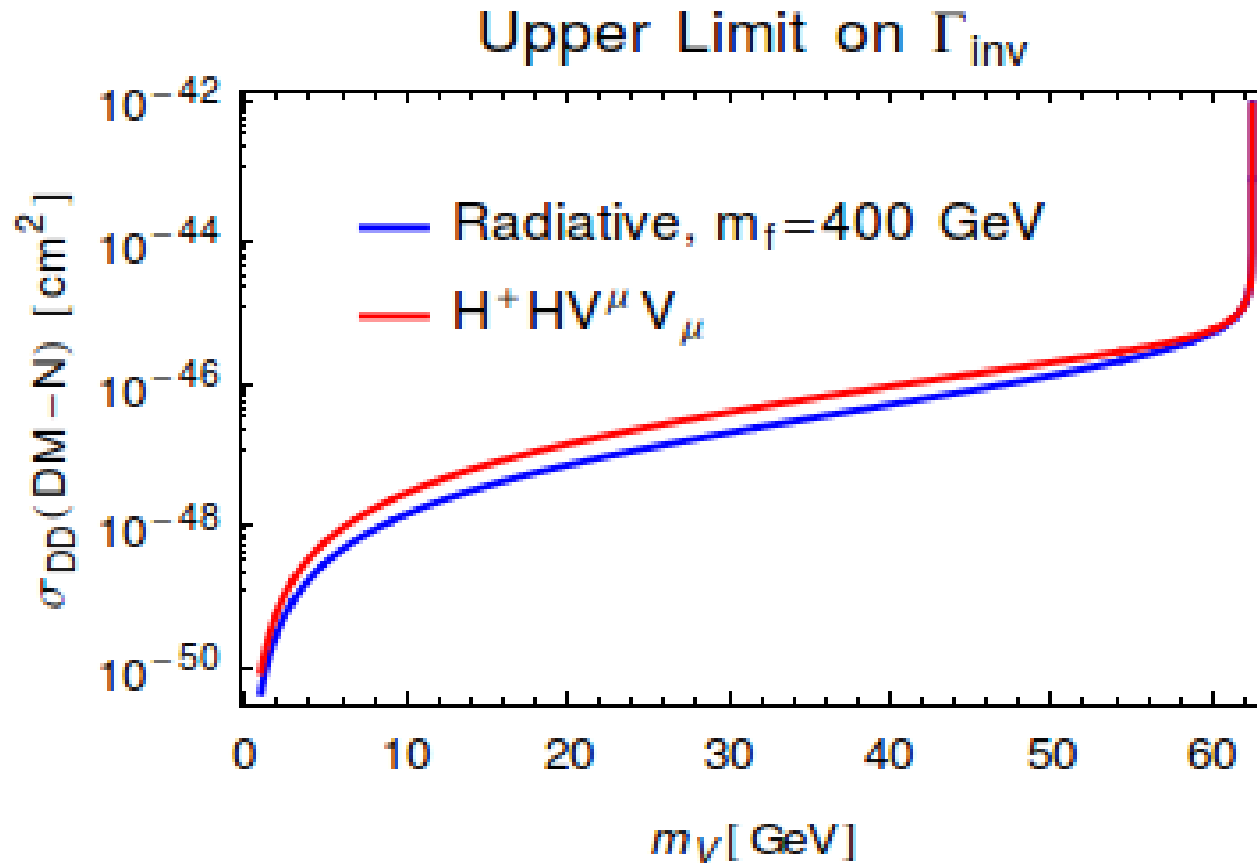
for small  $m_V$ ,  $|B| \sim m_V^2$

$$\sigma(VN \rightarrow VN) = \frac{1}{4\pi m_h^4} \left( \frac{f_n}{v} \right)^2 \left( \frac{m_N^2}{m_N + m_V} \right)^2 \underbrace{|B - Am_V^2|^2}_{\text{blue}}$$



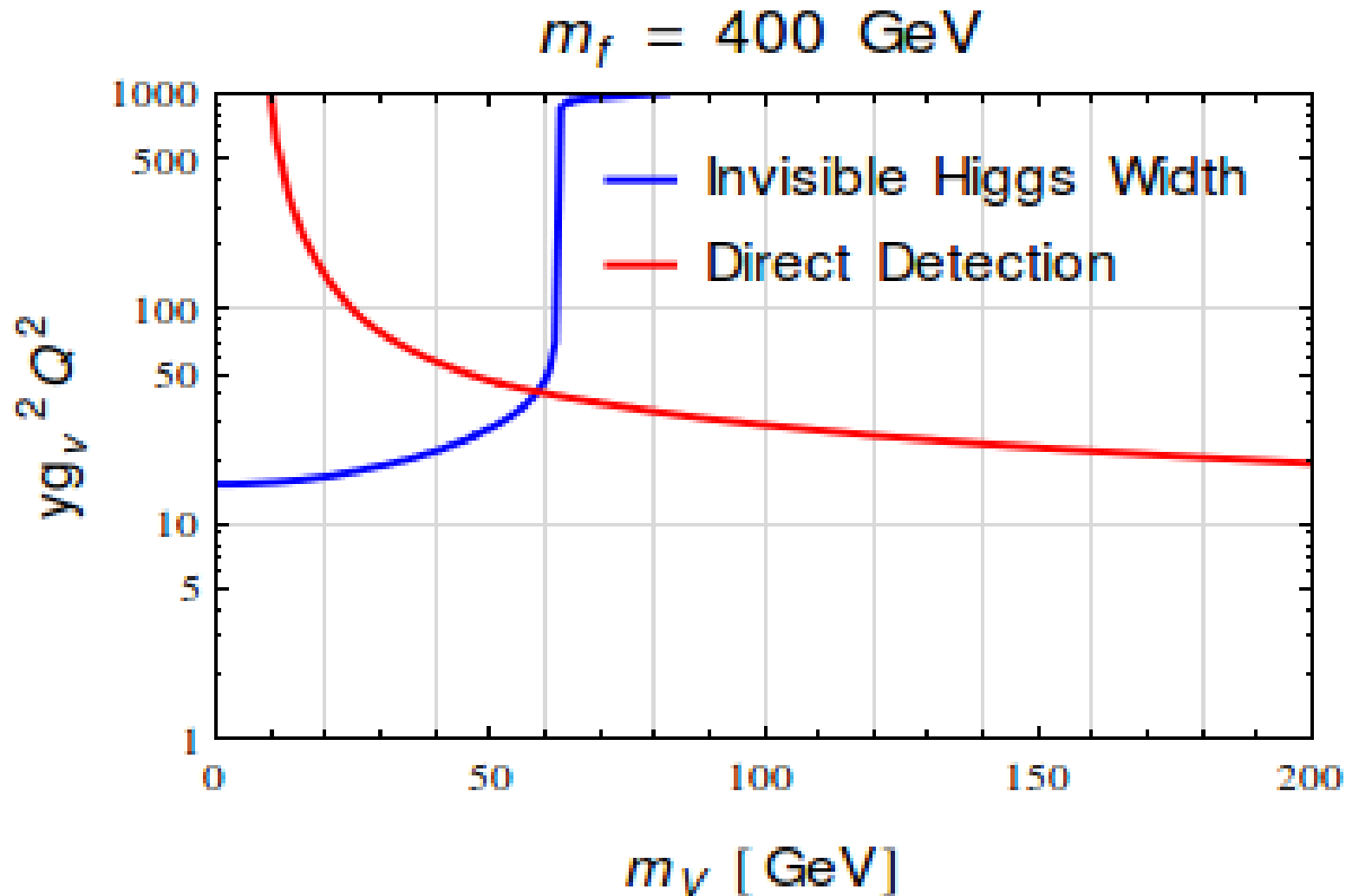
for  $m_V \rightarrow 0$  :  $|B| \rightarrow 0$ ,  $|A| \rightarrow \text{constant}$

# Two wrongs $DO$ make a right

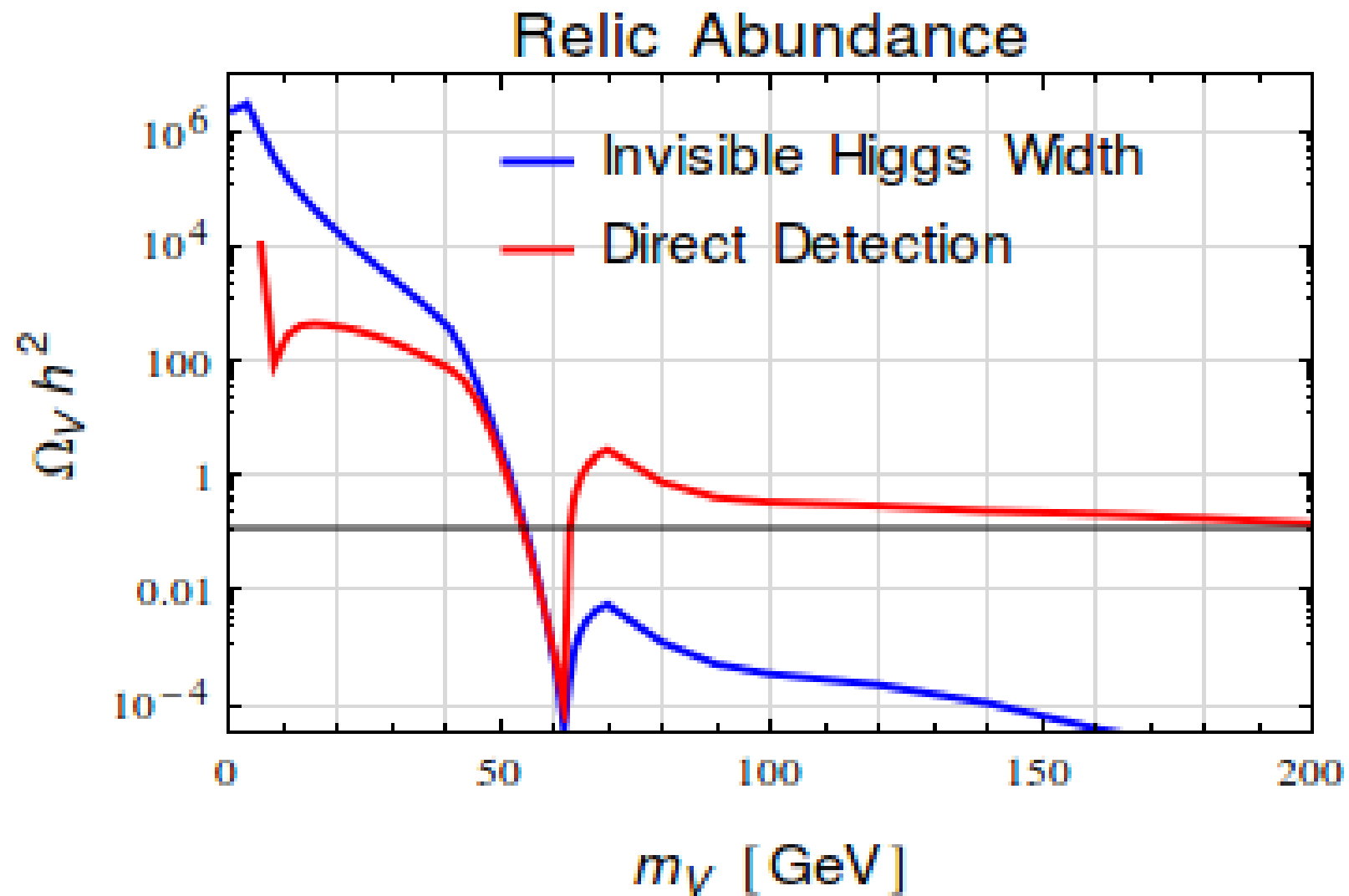


(taking ATLAS 14TeV 300fb-1 90%CL sensitivity:  $\text{BR}(h \rightarrow \text{inv}) < 0.19$ )

ATLAS Collaboration arXiv:1402.3244



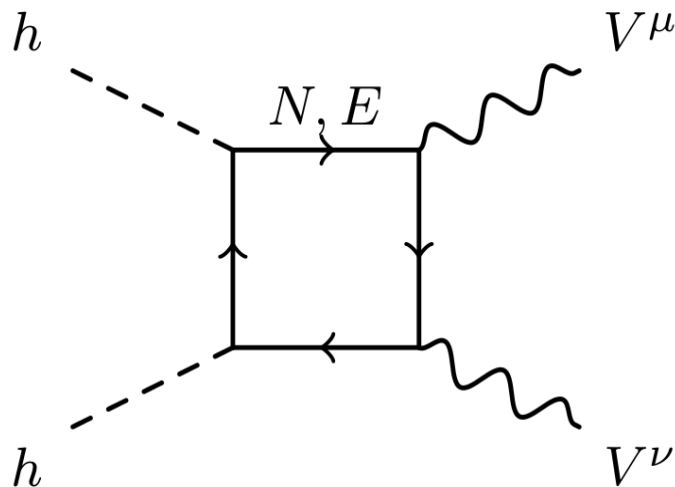
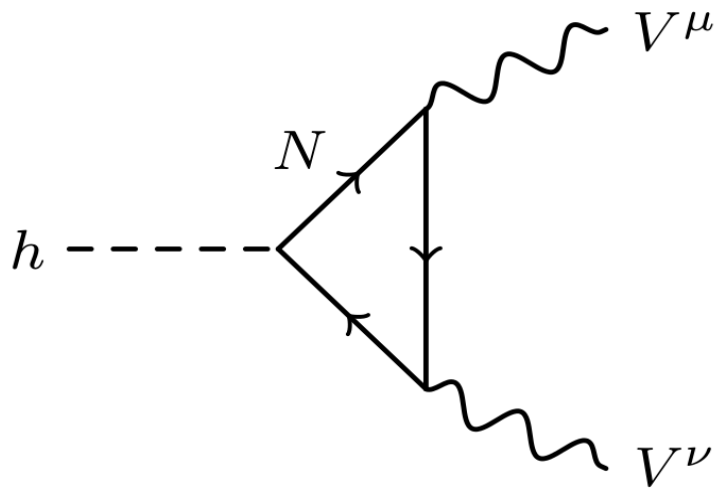
- Invisible Higgs width: VBF Higgs (CMS Collaboration [arXiv:1404.1344])  
including off-shell Higgs contributions (Endo et.al. [arXiv:1407.6882])
- Direct Detection: LUX Collaboration [arXiv:1310.8214]



# Necessity for Full Matter Content

- If the two heavier states are not much heavier than the first
- Description of all box diagrams, which allow other annihilation channels for large DM mass as well as photon lines
- Higgs couplings aren't diagonal, so Direct Detection and Collider constraints may be further suppressed

# Loops in Full Theory



- Triangle:
  - Only diagonal Higgs couplings contribute
  - Only neutral fermions
  - Easily done by hand
- Boxes:
  - Also:  $WW, ZZ, \gamma\gamma, hZ, \gamma Z$
  - All fermions contribute
  - Use software for evaluation

# Implementing Loops in Relic Abundance

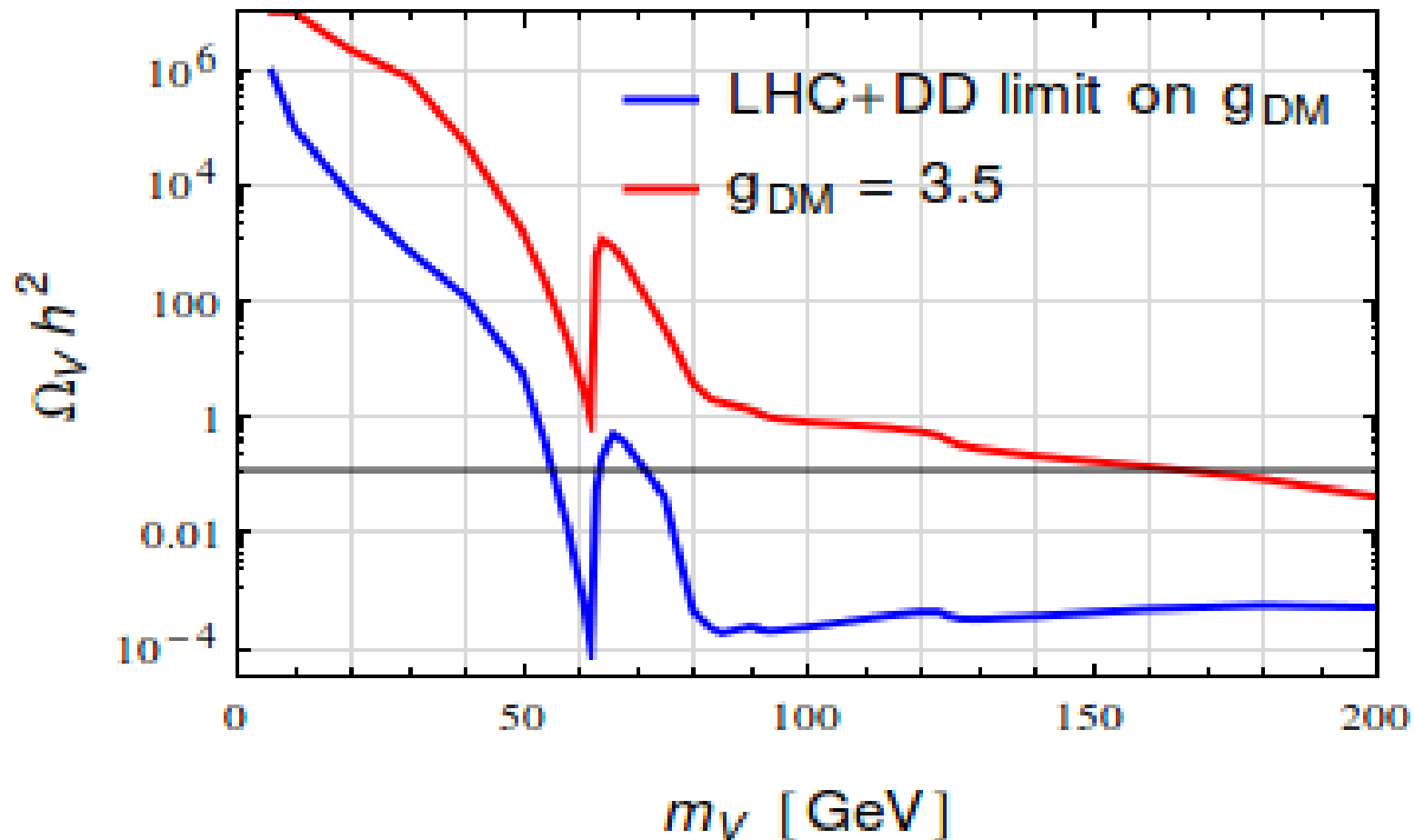
- No numerical packages do this for non-SUSY models
- Developed code to integrate two packages:
  - MicrOmegas: tree level Relic Abundance calculator
  - Feynarts/FormCalc: Loop level matrix element tool
- Looking to generalize and automate this implementation

# Preliminary Sample Point

$$m = 300 \text{ GeV}, \quad m_n = 800 \text{ GeV}, \quad y_\psi = 0, \quad y_\chi = 2.0$$

$$(M_{N1} = 943 \text{ GeV}, \quad M_{N2} = 214 \text{ GeV}, \quad M_{N3} = 357 \text{ GeV})$$

## Relic Abundance with Boxes



# And now for something completely different.....

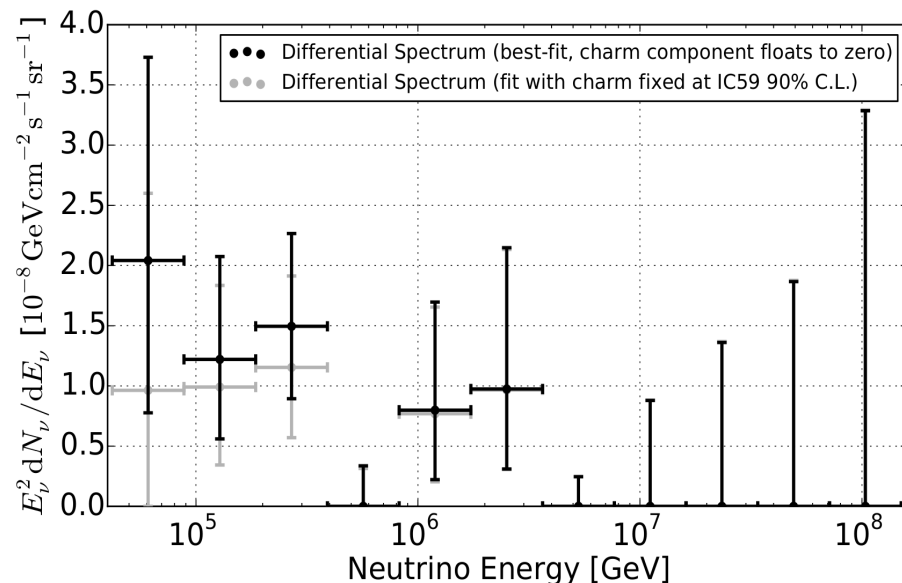


# Searching for MeV-Scale Gauge Bosons with IceCube

[arXiv:1507.03015](https://arxiv.org/abs/1507.03015)

In collaboration with:  
Dan Hooper

# UHE neutrinos at IceCube

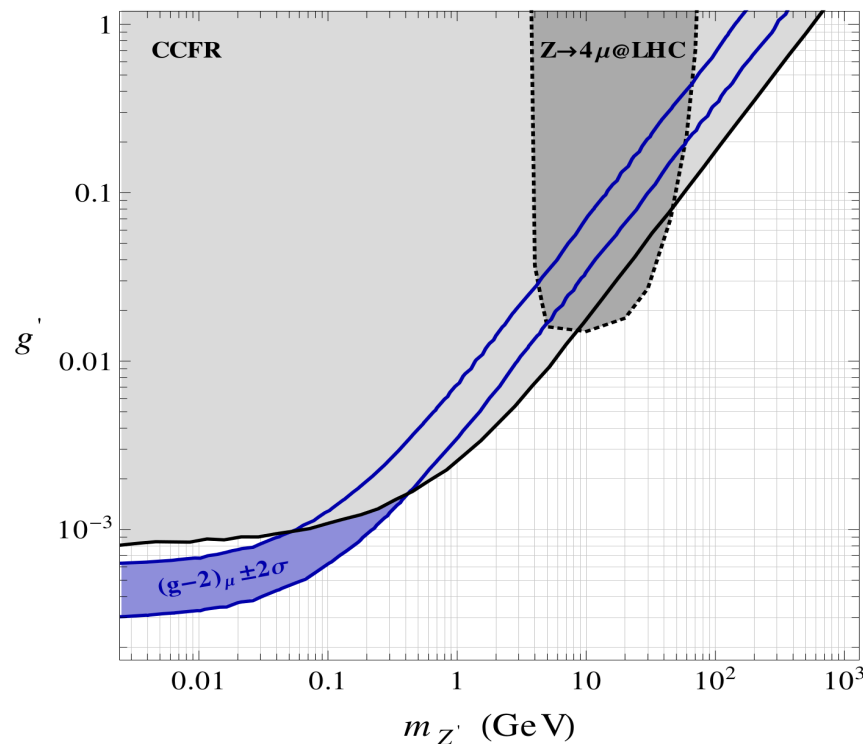


IceCube Collaboration [arxiv:1405.5303](https://arxiv.org/abs/1405.5303)

- 37 events with energies ranging from **30 to 2000 TeV**
- Possibly due to extragalactic sources
- Try to capitalize on these high energy neutrinos rather than understand their source

# Case Study: $(g-2)_\mu$

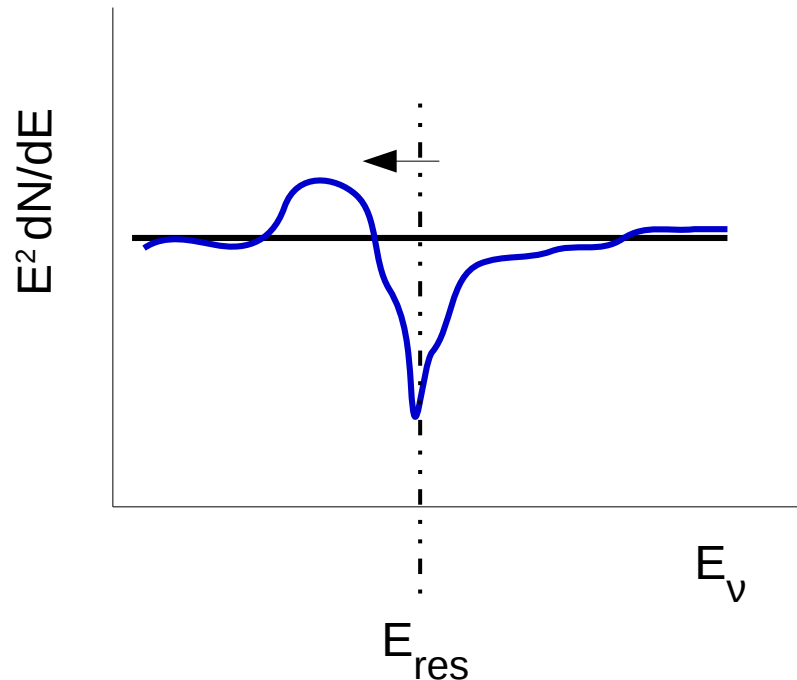
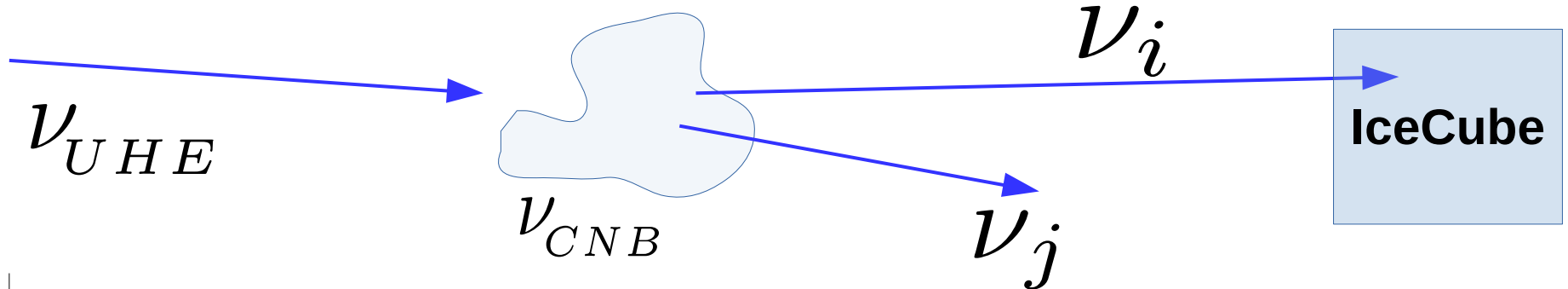
- $\Delta a_\mu$ :  $3.6\sigma$  deviation between measurement and SM prediction [PDG Phys.Rev. D86, 010001 \(2012\)](#)
- Possible solution:  $U(1)_{\mu-\tau}$



[Altmannshofer et.al. arXiv:1406.2332](#)

- $M_{Z'} \sim 1-100$  MeV still allowed by trident experiments

# Scattering with Cosmic Neutrinos



$$\mathcal{L}_{Z'\nu} = g_{Z'} Q_{\alpha\beta} Z'_\mu \bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta$$

$$E_{res} \approx \frac{m_{Z'}^2}{2m_\nu}$$

for  $E_{res} \sim 100$  TeV and  $m_\nu \sim 0.1$  eV

$$m_{Z'} \sim 1 - 100 \text{ MeV}$$

# Technical Details

$$-(1+z) \frac{H(z)}{c} \frac{d\tilde{n}_i}{dz} = \underbrace{J_i(E_0, z)}_{\text{Source Term}} - \underbrace{\tilde{n}_i \sum_j \langle n_{\nu j}(z) \sigma_{ij}(E_0, z) \rangle}_{\text{Scattering term}} + \underbrace{P_i \int_{E_0}^{\infty} dE' \sum_{j,k} \tilde{n}_k \left\langle n_{\nu j}(z) \frac{d\sigma_{kj}}{dE_0}(E', z) \right\rangle}_{\text{Regeneration term}}$$

**Source Term:** source distribution and redshift evolution

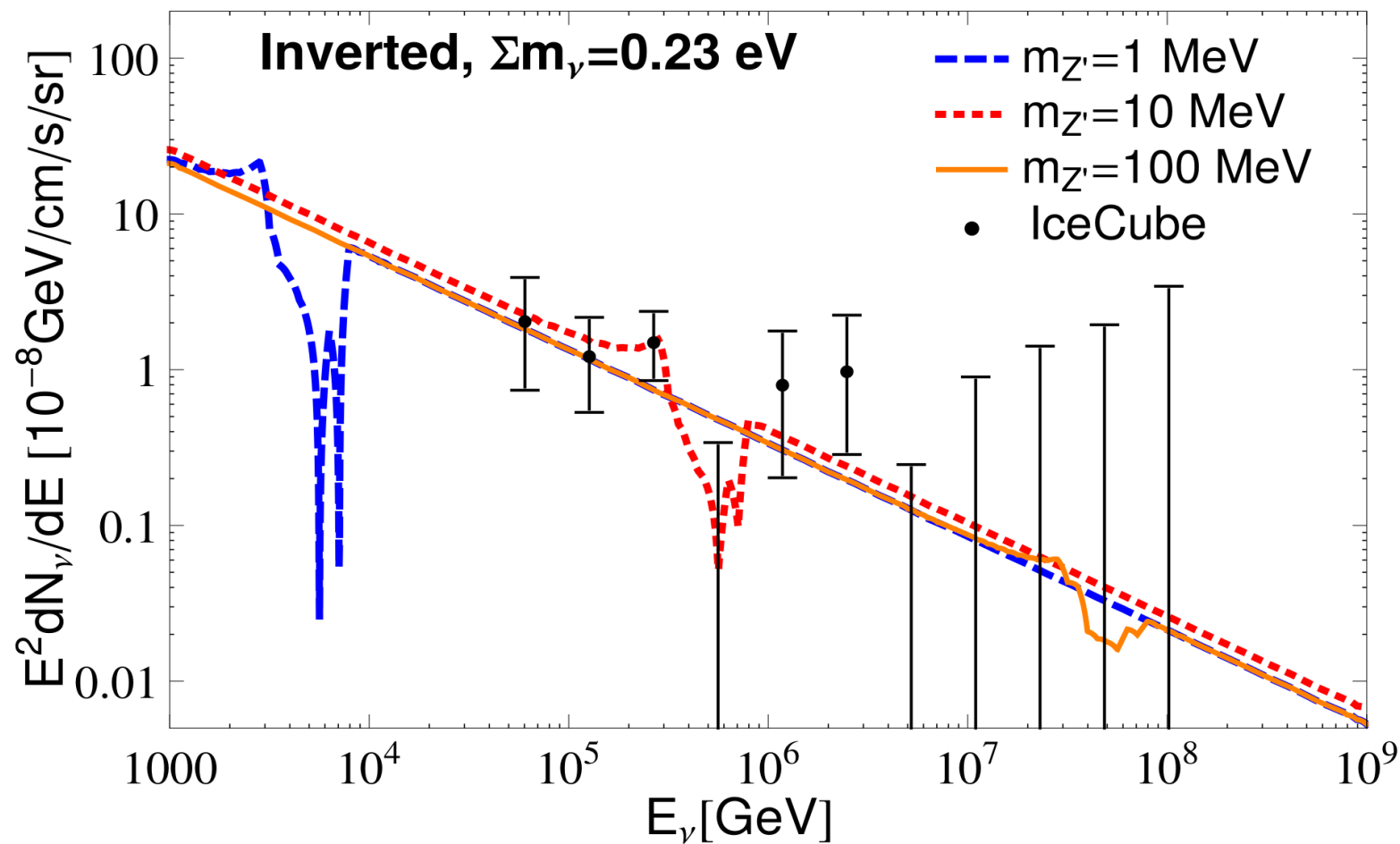
**Scattering term:** modeled as absorption

**Regeneration term:** from scattering products

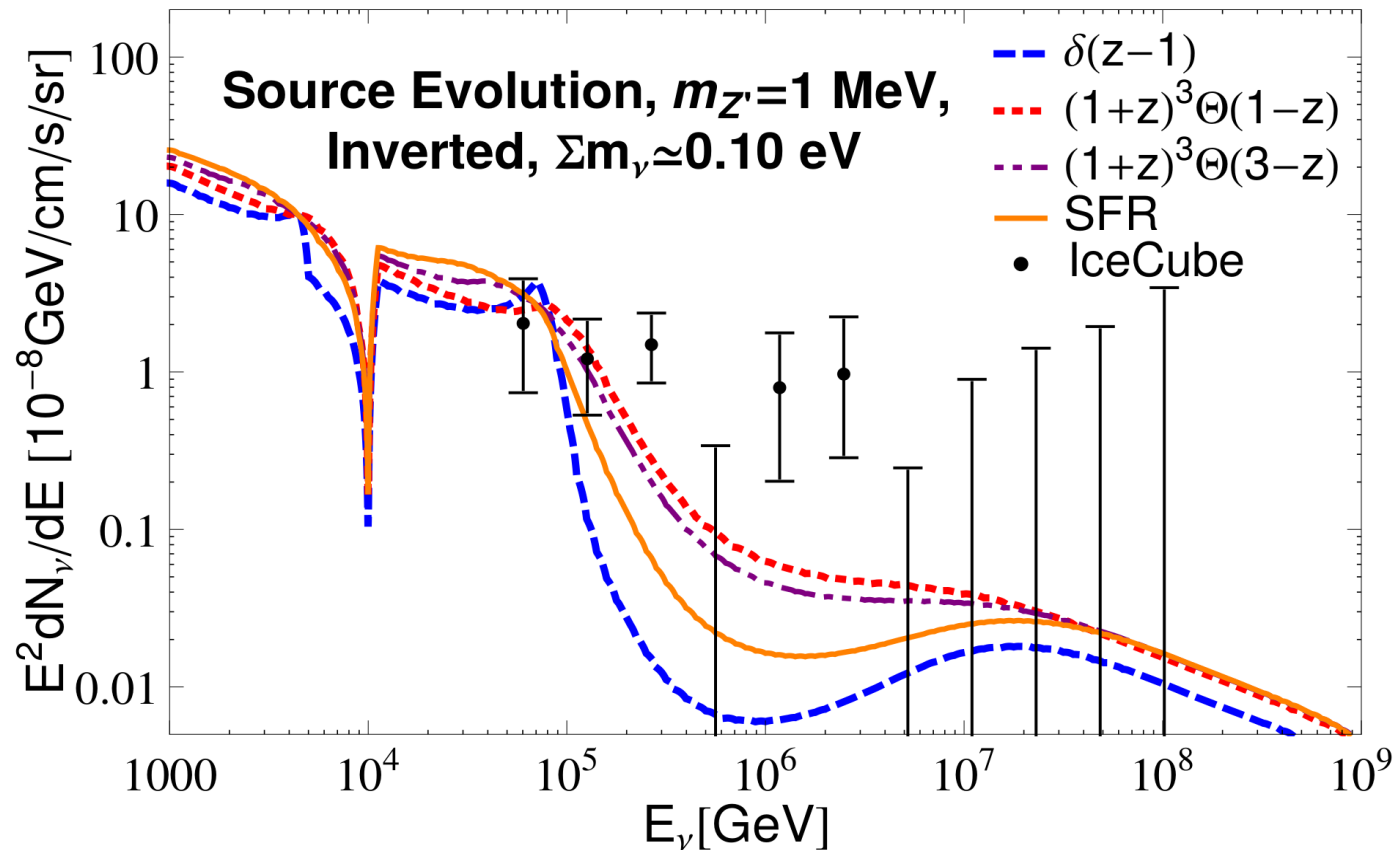
Thermal distribution of CNB is taken into account

Assuming the source has a constant comoving density

Inverted Hierarchy, with maximal neutrino mass sum



# Various Source Terms



- Relatively insensitive to source distribution:
  - Neutrinos produced at lower redshift contribute most to total measured flux
  - Structures formed at high redshift tend to be washed out by neutrinos regenerated at lower redshifts

# Summary & Conclusions

- Vector DM Higgs portal
  - Should be treated as EFT
  - Viable UV completions can be constructed for the Vector portal
  - Relic abundance is difficult to get with the vector portal. Though including mixing and loop level processes can help.
- MeV Gauge Bosons at IceCube
  - While not overly sensitive to the exact source evolution, we need:
    - a better understanding of the CNB
    - more precise measurements of neutrino properties
    - a better understanding of the UHE sources
    - More IceCube data!

Thanks!  
Questions?